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DPSSLs: Status and Prospects for Materials Processing

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DPSSLs: Status and Prospects for Materials Processing

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Abstract: The pricing of high power diode arrays, and the status and prospects for high power, high brightness Nd:YAG and Yb:YAG DPSSLs are reviewed.

1. Introduction

The technical development of high power, efficient one and two-dimensional diode arrays in the past few years has, in turn, enabled the development of kilowatt class diode-pumped solid state lasers (DPSSLs). Today, a centimeter long diode bar array can produce over 60 watts of CW power, at >45% efficiency, and with a lifetime in excess of 20,000 hours [1]. The continuous improvement in pump diode bar array performance characteristics (power, efficiency, lifetime, etc.), combined with the slowly expanding commercial market volume for high power diode pumps, has resulted in a sustained decrease in the price per watt for practical pump arrays. Scifres [2] reported that diode price per watt has been declining at an annual rate of 60% (see Figure 1), and is approaching a price point ($10/watt) that will allow for a significant market expansion of kilowatt class DPSSLs in the next decade for industrial materials processing applications.

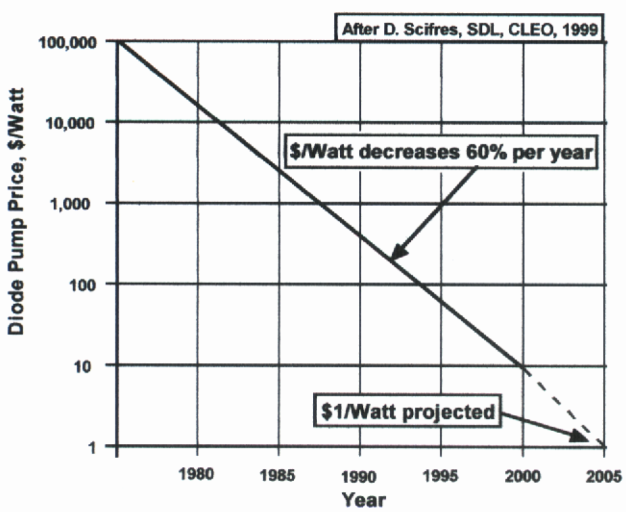

Figure 1. Diode pump pricing trend (Scifres [2]).

In general terms, three distinct types of high power DPSSLs have received significant development attention in the past year: Nd:YAG DPSSLs [3-8], Yb:YAG [9-11], and double-cladded Yb fiber lasers [12]. Emphasis has centered on scaling output power into the kilowatt regime, while retaining a relatively high beam quality (relatively low values of M^2 or mm-mrad beam product). This paper will limit discussion to high power DPSSLs, with emphasis on Yb:YAG DPSSLs since more detailed accounts of Nd:YAG DPSSLs will be given in the symposium by others. The review of Yb:YAG DPSSLs includes design considerations imposed by the Yb^{3+} laser ion, performance levels recently achieved using thin disk, end-pumped rod, and side-pumped rod laser configurations, and future challenges and prospects.

2. High Power Nd:YAG DPSSLs

Kilowatt class Nd:YAG DPSSLs have now been reported by Lawrence Livermore National Laboratory (LLNL), TRW Inc., Rofin-Sinar, the Fraunhofer Institute for Laser technik, TU Berlin, and Fanuc. Depending on the form of the gain medium (rod or slab), and on the details of the pumping and gain medium cooling geometry, beam quality M^2 values range from several 10's to ~3, the better beam quality being achieved at lower power levels. Figure 2 shows a photograph of the commercial NdYAG DPSSL developed by Rofin Sinar.

Figure 2. Rofin-Sinar Nd:YAG DPSSL [7].

Using a maximum pump power of ~3.5 kW, a maximum output power of 1.15 kW is obtained, but with a substantial M^2 value. Under reduced pumping, an output power of 820 watts is obtained with a beam quality value of less than 12 mm-mrad. This unit is now being utilized industrial settings for various materials processing applications [7]. Higher power units are being introduced.

3. High Power Yb:YAG DPSSLs

High-power, high-brightness Yb:YAG DPSSLs have been under development for several years now, primarily at LLNL by R. Beach and co-workers, at the Institut fuer Strahlwerkzeuge, Stuttgart University by A. Giesen and co-workers, and at Raytheon (formerly, Hughes Research Laboratories) by H. Bruesselbach and co-workers. With the commercial availability of high power 940 nm diode pump sources (single bar, 2-D stacked arrays, and fiber bundles), Yb:YAG DPSSLs with output powers of hundreds of watts to over a kilowatt are now being reported [9-11].

The Yb^{3+} laser ion operates at room temperatures in a quasi-three-level laser scheme, and design of the laser has to take into account the (saturable) resonance absorption loss at the laser wavelength. The Yb^{3+} laser energy level structure results in a quantum energy defect (percentage difference between pump and laser photon energies) of only 9%, compared to 24% for the Nd^{3+} ion. However, this favorable Yb^{3+} characteristic is more than offset by the relative laser transition cross-sections: $2x10^{-20}$ cm^2 for Yb:YAG compare to $3x10^{-19}$ cm^2 for Nd:YAG. Thus, the specific thermal loading will be several times higher in a Yb:YAG DPSSLs than that in a Nd:YAG DPSSL, when both are pumped so as to have the same gain coefficient. For this reason, the management of thermal gradients and waste heat removal dominates the design of high-power, high-brightness Yb:YAG DPSSLs. Furthermore, the quasi-three-level characteristic of the Yb ion, and its generally smaller laser transition cross-section usually translates into a requirement for considerably brighter pump sources than the brightness of pump sources customarily used for Nd:YAG DPSSLs.

To achieve high power and brightness from a Yb:YAG DPSSL, Giesen and co-workers at the University of Stuttgart have developed the "thin disk" [13] design approach. Here, a thin (<1 mm thick) YAG disk doped with ~10-15% Yb is pumped in a small spot (~1-2 mm diameter) nominally perpendicularly to the face of the disk. A high reflectivity mirror (at both the 940 nm pump, and the 1030 nm laser wavelengths) is placed on the disk face away from the incident pump. This mirror serves as one the mirrors of a laser resonator cavity. The other cavity mirror is a curved output mirror, placed on an axis perpendicular to the disk face, centered on the pumped spot, and having a transmissivity at the laser wavelength that optimizes the output power.

In the thin disk laser, waste heat generated in the disk is extracted through the back high-reflectivity mirror, to an actively cooled submount holding the laser disk. The key feature of the thin disk design approach is that this cooling geometry constrains resulting thermal gradients to lie essentially parallel to the laser resonator axis. Consequently, thermal focussing by the gain disk is greatly reduced, facilitating the achievement of high beam quality (with proper resonator cavity design). Additionally, this high beam quality can be obtained over a wide range of pump and output powers, a feature not easily obtained in strongly pumped end- or side-pumped Yb:YAG DPSSLs. Recent improvements in thin disk Yb:YAG DPSSL performance has been achieved through the use of a novel pumping optical system [9] that provides for up to 16 passes of the pump radiation through the (optically thin) disk gain medium.

Figure 3 shows some of the recent performance characteristics reported for the thin disk Yb:YAG DPSSL using this new optical pumping arrangement. For a cooling fluid temperature of 15 °C, a TEM_{oo} mode output of more than 30 watts is observed with the resonator parameters given in Figure 3, and the M^2 value remains close to unity throughout the full range of pump power utilized. The obtained TEM_{oo} mode power is only slightly less than the highly multimode power obtained with the different resonator cavity parameters indicated in Figure 3. For TEMoo mode operation, the optical-to-optical power conversion efficiency is >50%.

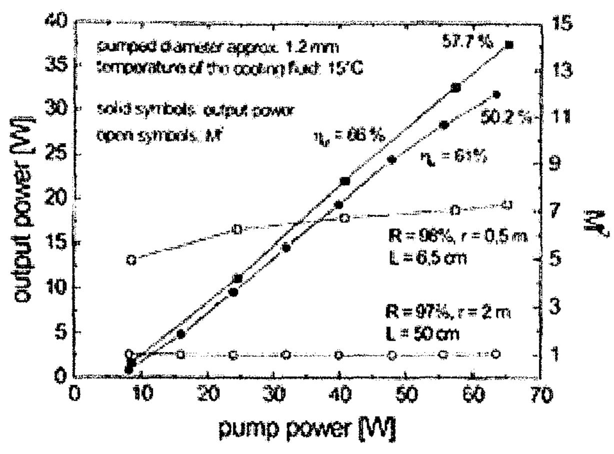

Figure 3. Output power and M^2 values vs. pump power fir a thin disk Yb:YAG DPSSL [9].

This basic design of the thin disk Yb:YAG DPSSL has been engineered by the Trumpf/Haas-Laser Company in Germany, in the form of a prototype industrial product shown at the recent Munich Laser show. This laser produces

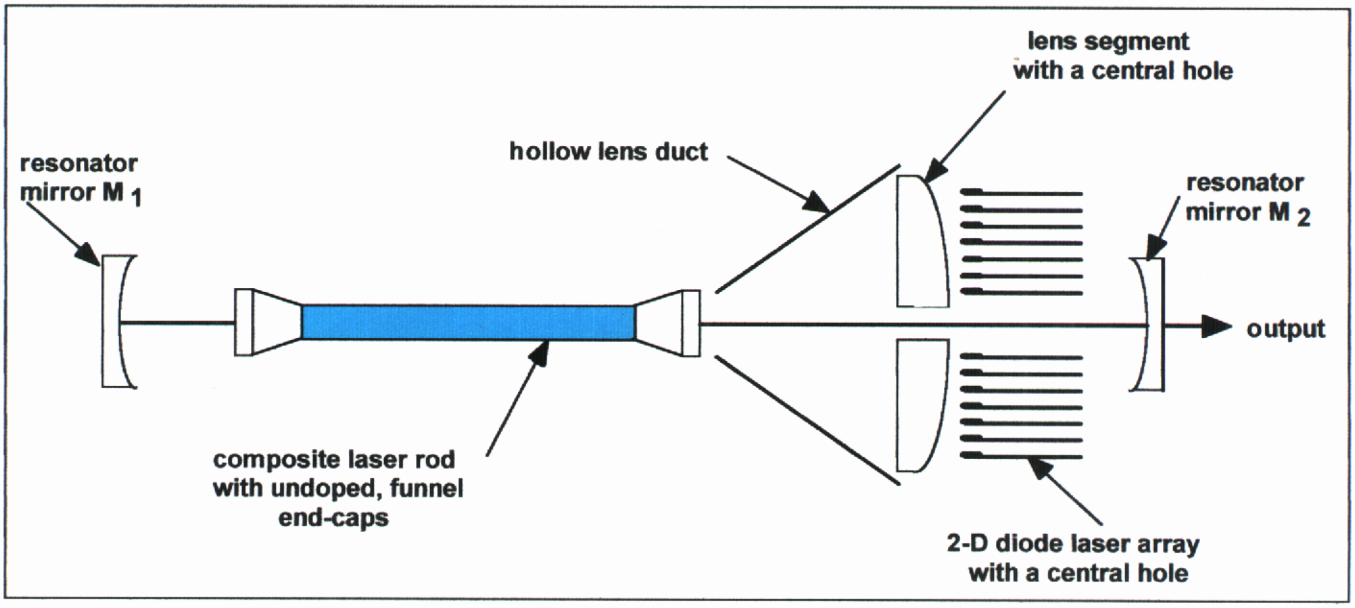

Figure 4 Hollow lens duct, end-pumped Yb:YAG DPSSL, after Honea and Beach [11].

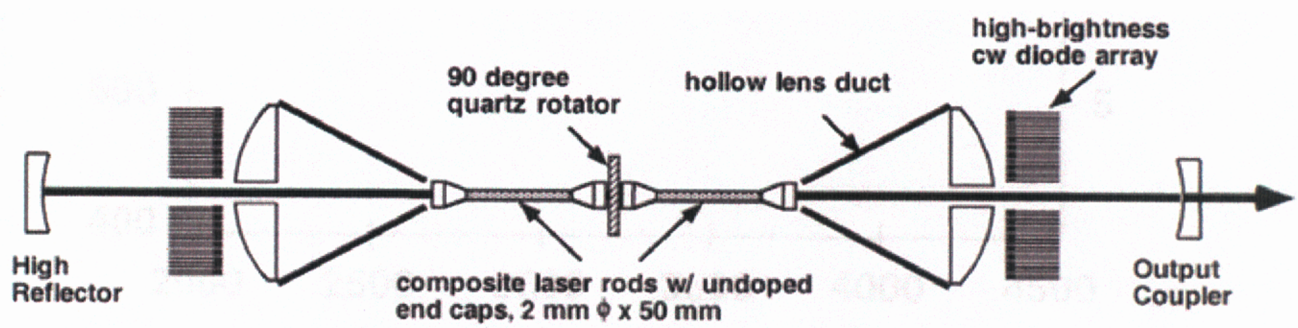

Figure 5. Schematic diagram of the dual rod Yb:YAG DPSSL with birefringence and bifocusing compensation.

a kilowatt of output power with a moderately low M^2 value, sufficient for performing many high power materials processing applications. Apparently, to achieve the kW output power, two thin disk gain elements were incorporated within a single laser resonator cavity. It is reported that the most difficult engineering challenge associated with the thin disk design concept is the operating reliability and lifetime of the back plane mirror, as it is subjected to high thermal-mechanical stress and extensive thermal cycling.

An alternative approach to scaling the power and brightness of Yb:YAG DPSSLs is the "end-pumped" configuration, substantially developed by Beach and co-workers at LLNL [14]. In this approach, the pump radiation from a 2-D stack of laser diode bars is collected by a non-imaging "lens-duct", and transported by the lens duct into one end of the laser gain rod. Usually, the ends of the Yb doped YAG gain rod are diffusion bonded to undoped shaped end- caps that reduce the thermally induced stresses in the end regions of the gain rod, and also suppress the onset of parasitic modes that would oscillate in simple gain rod.

Because incident pump power has a relatively long length of gain medium in which to be absorbed (compared with transverse pumping of a relatively thin rod), the waste heat generated in the rod can be distributed over a relatively large lateral surface of the gain rod. Also the Yb doping level can be reduced (compared to the transverse pumped rod), which reduces the resonance absorption loss at the laser wavelength.

In the first demonstrated lens-duct, end-pumped Yb:YAG laser, the pumped end surface of the Yb:YAG gain rod served as the high-reflecting mirror of the laser resonator. A high-performance dichroic mirror coating is required on this surface to highly transmit pump radiation at 940 nm, while reflecting highly at the nearby 1030 nm laser wavelength. This coating is difficult to make, especially for high power operation. To overcome this difficulty of a lens-duct end-pumped Yb:YAG DPSSL, Honea and Beach [11, 15] introduced the **hollow** lens duct, in which the tapered TIR surfaces of a solid lens duct are functionally replaced by the tapered polished surfaces of a machined metal body. Additionally, the 2-D diode pump array is constructed with a small hole placed in the center of the array, providing for a line-of-sight to run fully between the two mirrors of the laser resonator, through the pump array, hollow lens duct, and laser rod, as shown in Figure 4. Now, both ends of the laser rod can be accessed optically without the need for any dichroic mirrors in the cavity. Using this arrangement, Honea and Beach [11] were able to achieve a CW output power of over 450 watts, with an M^2 value of 3.7, at an optical-to-optical efficiency of 19.3%. The measured transfer efficiency of he hollow lens duct was 82%. Q-switched operation of a hollow lens-duct end-pumped Yb:YAG DPSSL was achieved by inserting an acousto-optic Q-switch in the resonator, and appropriately designing the resonator cavity mode waist (embedded Gaussian formalism) using strong pumping conditions [15]. A Q-switched output power of 183 watts was achieved at a pulse repetition rate of 5 kHz and with an M^2 value of ~2.4. The pulse energy and pulse duration under these conditions were 33 mJ and 73 nsec, respectively.

To further scale the output power of an end-pumped Yb:YAG DPSSL, while maintaining high beam quality, Honea and Beach [11] employed two laser rods and two hollow lens ducts, as shown in Figure 5. A 90° rotator was placed between the two rods at the center of the cavity to achieve birefringence compensation. Each 2-D diode array was capable of producing 2 kW of radiation conditioned pump radiation at 940 nm.

Figure 6 shows the CW output power obtained from this arrangement. Over a kW of output power was obtained with an M^2 of 13, and with an electrical-to-optical efficiency of 12.3%.

Q-switched operation of this dual-rod configuration was also obtained, using two acousto-optic Q-switches. A maximum Q-switched output power of 532 watts was obtained at a pulse repetition rate of 10 kHz, with a pulse duration of 77 nsec, and with an M^2 value of ~2.2.The optical-to-optical conversion efficiency was 17%. This Yb:YAG DPSSL is an exceptionally high-brightness, high power Q-switched laser and is quite compact. It has excellent pulse properties for high-speed precision drilling applications.

Side-pumped rod Yb:YAG DPSSLs are also being developed, by H. Bruesselbach and co-workers [16.17]. A kilowatt output power level has recent been reported [17], but no information regarding output beam quality has been given.

In aggregate, the advances in power, beam-quality, and efficiency of Yb:YAG DPSSLs in the past year are impressive. Being pumped with high reliability InGaAs laser diode pump arrays at 940 nm, it is expected that cost competitive industrially hardened Yb:YAG DPSSLs will appear in the next year or so, providing the first real alternative to the more mature Nd:YAG DPSSLs.

4. Acknowledgement

The work on end-pumped Yb:YAG DPSSLs summarized in this paper was performed by several colleagues at LLNL, R. J. Beach, E. C. Honea, S. B. Sutton, C. M. Bibeau, P. V. Avizonis (Boeing Company) and S. A. Payne. Their efforts are greatly acknowledge. A detail account of their work will appear in a forthcoming SPIE volume recording the Advanced High Power Lasers and Applications (AHPLA) Conference, Osaka, Japan, November 1-5, 1999. This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

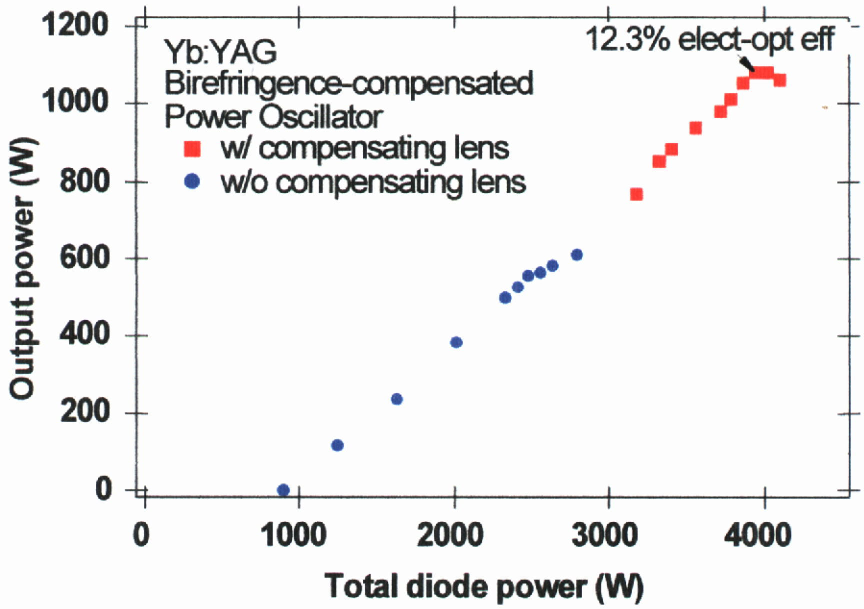

Fig. 6. Plot of measured cw output power from our birefringence and bifocusing compensated dual-rod Yb:YAG laser. At the high power end, cavity stability required the placement of a negative lens in the resonator between the two Yb:YAG laser rods.

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